The Need for Demand side Fast Frequency Response and Inertia in a Zero Carbon Grid

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March 19, 2022

Contents

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1 Introduction

The UK government has committed to the target of becoming net zero by 2050. This commitment is just one of the many similar such commitments to net zero made by governments all around the world. In this essay I will explore how a truly zero carbon grid could be realised with current technology, and with this framework highlight the fundamental trade-off and constrains which must be reconciled as a part of this transition.

2 Capacity Factor (CF)

Capacity factor [1] is defined as the total energy generated over a period of time divided by the theoretical maximum as specified by it's nameplate rating.

$$CF = \frac{E_{total}}{E_{max}} \tag{2.1}$$

CF is a useful high level metric and can be though of as the degree of utilisation of a given generator. Depending on the generation type, the capacity factor will vary due to factors such as:

- Intermittency of generation
- Outages/Maintenance
- Political incentivisation/dis-incentivisation
- Curtailment due to overcapacity or network constrains

From Figure 2.1 we can see that capacity factor varies substantially between generation types. Wind and solar energy for example have a much lower CF than other generation. This can of-course be explained by the intermittent nature of the energy source, for example a wind turbine might be able to generate

[1] Also known as load factor

8MW at high wind-speeds, however wind-speeds vary substantially throughout the day. Interestingly a noticeable difference exists between onshore and offshore wind, pointing to an advantage of offshore farms, that being greater consistence of generation.

Nuclear energy on the other hand has a relatively high capacity factor of ≈60%[2], this is largely because, as will be discussed further in Section 3.0.3, the key mechanism to lower cost of electricity is to increase CF.

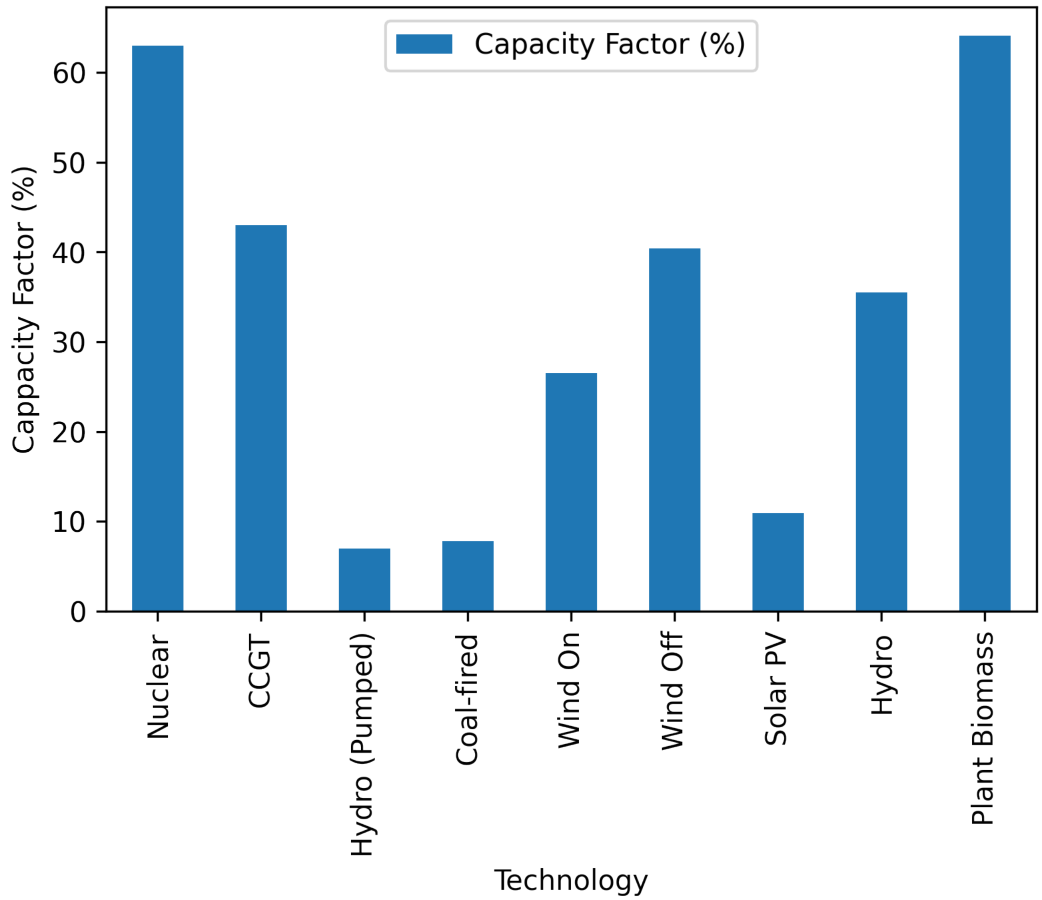

Figure 2.1: *Breakdown of capacity Factor by Generation Type for 2019, Data Sourced from UK government [1, 2], Tabular data in Appendix Section 9.4.*

3 Levelized Cost of Electricity (LCOE)

3.0.1 What is LCOE

Since we have established Levelized cost of electricity (LCOE) is defined simply as the total cost of building, running and decommissioning an energy generation asset divided by it's lifetime generation cost.

$$LCOE = \frac{\text{Lifetime Cost (\$)}}{\text{Lifetime Production (KWh)}} = \frac{C_{Life}}{E_{Life}} \tag{3.1}$$

[2]It should be noted that this capacity factor is substantially below the typical value which is often upwards of 80% however given the ageing nuclear plants in the UK the past several years have seen substantial outages for maintenance, and plants coming offline. In this sense this capacity should be seen as artifactualy low.

This is a vital metric for comparing the cost effectiveness and profitability of a given generation source. By accounting for profit margins and transmission/distribution use of system fees, this metric may also give a very rough insight into the likely end cost of energy to the consumer assuming a relatively competitive energy market.

3.0.2 LCOE Breakdown by generation Type

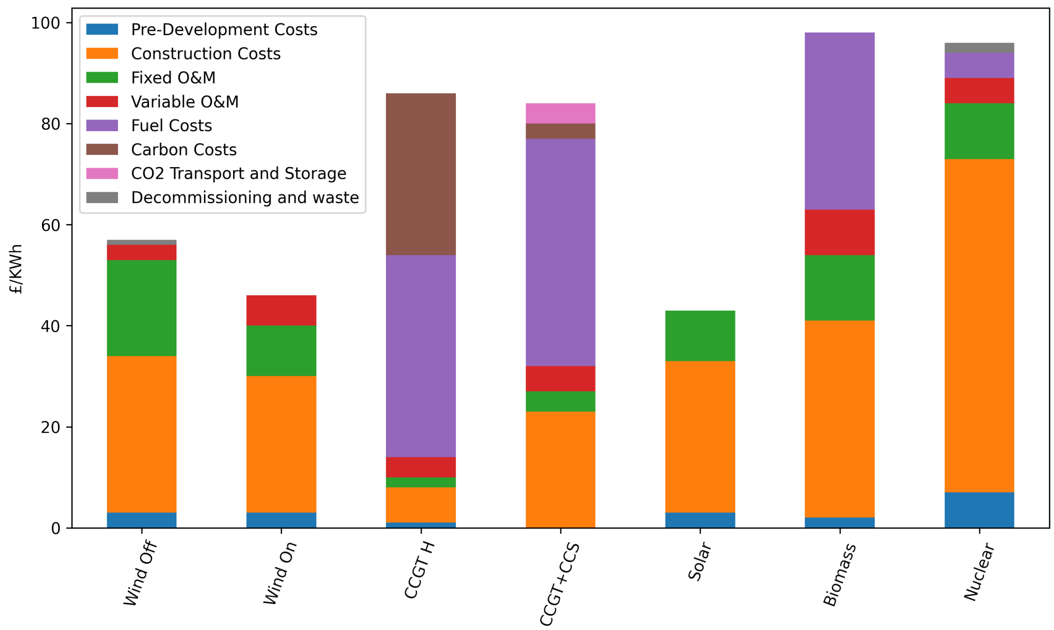

Figure 3.1: *Levelized cost Estimates for Projects commissioning in 2025, £/MWh (Data is sourced from UK Government Figures Published in 2020[3])*

3.0.3 LCOE vs Capacity factor

Choosing the optimal mix of energy generation is not simply a case of electing the lowest LCOE since the LCOE itself will be a function of the capacity factor and this capacity factor will be affected by the type of grid. This can be shown by assuming that the operational period (t_{hours}) and the levelized fuel cost is relatively fixed[3], we can then rearrange Equation 3.1 into 3.2 (see Appendix 9.1 for full derivation).

$$LCOE = \frac{C_{Fixed}}{S_{Base\ kW} \times t_{hours} \times CF} + C_{Fuel(£/kWh)} + C_{carbon(£/kWh)} \tag{3.2}$$

Examining 3.2 see that generators trying to minimise LCOE roughly have only one degree of freedom [4], that being capacity factor. Indeed we see in generation like Nuclear energy where fixed costs are high and fuel +carbon costs are low, capacity factors are often very close to 1 and even then the LCOE is relatively high relative to other generation types (see 3.0.2). Wind and solar energy on the other hand have no fuel or carbon costs and relatively low LCOE, even with substantially lower capacity factors than other generation. This is because the cost per installed kW capacity (C_{Fixed}) for wind and solar is so low that is compensates for this low CF.

[3]It should be noted here that this is a very high-level analysis with many implicit assumptions, among them the assumption of fixed lifetime for a given generation type : This means that OEM costs which are roughly speaking a function of lifetime and capacity factor can be considered fixed costs.

[4]This ignores of course all of the other ancillary service which may be supplied on top of just energy.

4 Future Space Heating Demand

A critical challenges in the transition to net zero is decarbonising residential space heating. As of Tue, 15/03/22 the future of heating in the UK is still very unclear. Until recently the UK has relied on the abundant gas reserves of the north sea for the vast majority of it's heating needs. These reserves however are dwindling, and beyond being in carbon intensive, depending in imported natural gas is expected to incur increasing cost, not to mention poses a geopolitical vulnerability. It is thus no surprise that decarbonising heating has received substantial attention from the government.

The current policy of the UK government seems to be leaning in the direction of full electrification of heating using heat pumps in combination with altered building standards for improved insulation. This approach has been met with some scepticism on the grounds of high unit cost of heat-pumps and relatively limited uptake [`citation needed`]. It is the authors opinion however that these limitations may be mitigated though shared ownership of units or some form of district heating schemes.

Competing proposals have also been made to utilise the existing gas infrastructure instead with hydrogen generated through electrolyse rather than fossil fuel sourced gas [5]. This approach has the advantage of the relatively high energy density of hydrogen [6] potentially allowing for relatively low cost energy storage [`citation needed`]. The potential advantages of hydrogen have also attracted significant attention in the transport sector, seeing research in cars, busses, trains and even boats. When competing with electrical storage such as batteries, or pumped hydro, it is still very unclear which, if any technology will decisively win-out in these sectors. If this were to occur, it would likely substantial improve the economics of hydrogen for heating due to the potential to share infrastructure and in the benefits of research and commercial interest.

As such currently only two plausible scenarios exist for UK heating energy[7]:

1. Large scale Hydrogen gas network
2. Full Electrification using Heat-pumps

When considered from the point of view of the electrical energy network, these two options are both fundamentally consumers of energy, however the quantity and distribution of the load vary substantially in each case.

4.1 Current Natural gas demand

Natural gas demand will be used as a proxy for the UK's current heating demand. In 2019 the UK's total natural gas demand was ≈863 TWh, of this, ≈377 TWh was in the domestic, commercial and public sector [4]. This report will assume that the majority of this energy is used for space heating, meaning that this figure is a good proxy for the UK's total space heating energy demand that must be decarbonized through electrical means.

From Figure 4.1 It is noted that this sector, though the largest, still only amounts to ≈43% of total natural gas demand. With the exception of electrical generation, it is still largely unclear how many industrial uses of natural gas, for example the refinement of raw materials,will be decarbonised. A possibility is that net carbon syncs could trade their carbon capture capacity, or that these industries pivot towards zero carbon hydrogen. Both scenarios are likely to have substantial impacts on the network as a whole, however it is outwith the scope of this report to speculate future developments here so the influence of the remaining ≈25% (Losses, Other and Industry) will not be considered.

[5] Biogas may also be used, however it seems unlikely that biogas will ever become a dominant source of heating due to fundamental limitations in available bio-matter

[6] This is relative to the current energy density of Lithium Ion battery

[7] It is noted that at least transiently, the end result will likely be some combination of both

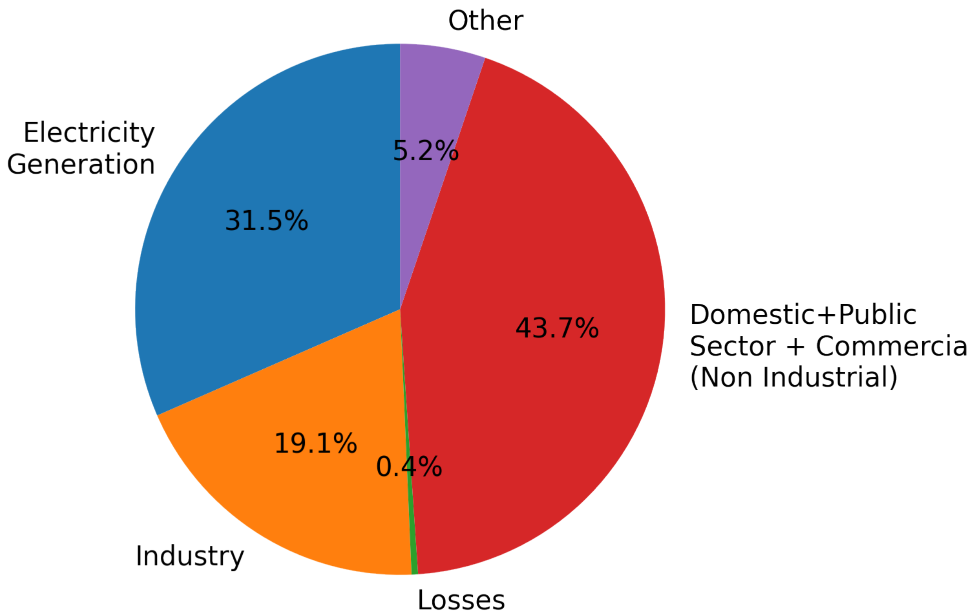

Figure 4.1: *UK Natural Gas Demand for 2019, Figures supplied by the UK government [4], Tabular Data in Appendix Section 9.6.*

4.2 Electrical Characteristics of Hydrogen Scenario

In the case of the large scale Hydrogen network, at least as much energy must be supplied electrically to the electrolyser producing the hydrogen fuel, as will be used by the consumer to heat. Since current alkaline fuel cell technology such as Cummin's HYDRLYZER can attain up to 70% efficiency [5] and there will be other energy losses due to compression and leakage [8], we may safely assume that the electrical energy required per unit thermal energy used will be at least $\approx$ **1.5**.

The key advantage of this scenario is of course the greater ease of storage[6]. As such demand can be assumed to be dis-patchable to a certain degree, as long as the correct net energy is delivered.

4.3 Electrical Characteristics of Heat pump Scenario

5 Constraints

To bound the problem we may set constraints on aspects of this proposed future grid to help narrow down the problem.

5.1 Cost of electricity

5.1.1 Breakdown of an energy Bill

A vital constrain when considering future energy mix is that the cost of electricity to the end user remain low enough so that consumers will have manageable heating bills. This means that on a \$/kWh[9] heat energy must cost less than or in the region of the existing cost of gas. From this and the typical COP of a consumer grade heat pump, an upper limit on the acceptable cost per kWh may be established. This can then be roughly translated in an upper limit on the total LCOE of the generation sources on the network. From Figure 5.1, we can see that the wholesale price of electricity, accounts for only $\approx$30% of the final bill.

[8] Hydrogen tends to be substantially more leaky due to it's atomic size

[9] \$/kWh is used for compatibility with the academic literature

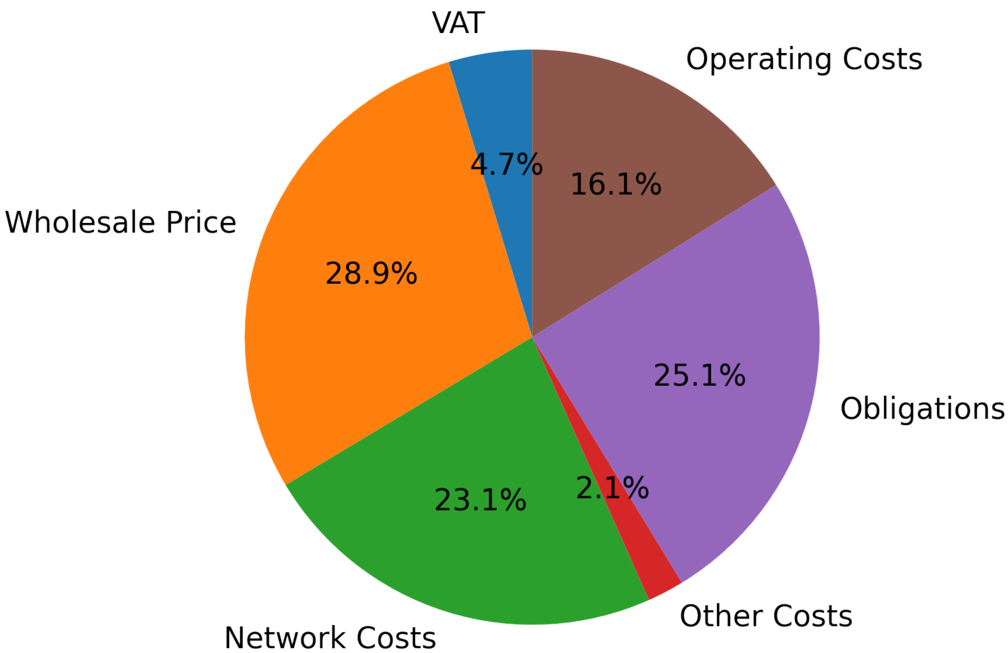

Figure 5.1: *Ofgem Estimated components of customer's energy bills from Ofgem [7]*

5.2 Consistency, Overcapacity and Energy Storage Trade-off

When faced with a highly variable energy supply one obvious degree of freedom is to oversize the system capacity. Though the minimum and maximum available generation would likely still vary with the same shape, the absolute value of the minimum would have increased meaning the absolute size of any generation shortfall, would be diminished. This has the obvious downside of resulting in a direct increase in costs due to the increased number/capacity of assets which would be directly be passed onto the levelized cost of electricity and thus the cost to the consumer. Where *reliability* is defined as the fraction of time that demand is less than the available energy, one would expect there would be diminishing returns on *reliability* for increases in capacity simply due to the statistical nature of renewable availability.

To fully derive the degree of capacity required to guarantee 100% energy fundamentally depends on the statistical variation of the available energy of the renewable resources and the total energy storage capacity on the network. Producing an accurate figure for this is near to impossible would require complex statistical modelling along with substantial knowledge assumptions regarding the energy storage capacity of the network, thus the calculation conducted here should merely be seen as proving a ballpark figure.

Through a comprehensive study of observed wind speed data from 66 sites across the UK and statistical analysis, Sinden [8] showed that that the seasonal average wind power availability varies by only approximately $\pm$ 10% of the yearly average. It was also shown that the total period of time per year where the entirety of the year where 90% of the UK experiences low wind is less than one hour.

For this analysis, Wind and solar data from the UK website gridwatch [9] for the year 2020-2021. By assuming that the entirety of the UK's wind resource is not curtailed due to [10]

meaning it would likely be require oversize Since a fundamental requirement of any stable grid be that reliability always be 100% (i.e. available generation $>$ demand)

[10]this may seem like a substantial assumption, but

It is therefore expected that for the lower cost generation sources such as solar and offshore wind, there will be substantial over capacity while the nuclear fission plants operate continuously at near full capacity.

6 Future Zero carbon Energy Mix

Forecasting the future energy mix is the subject of extensive debate and is sensitive to a huge variety of unpredictable factors and unknowns such as government policy, geopolitical developments, to disruptive technologies. This analysis however starts with the assumption that the UK grid is indeed to be truly decarbonized and attempts to reason how this might look with current technologies. In this section will investigate which combination of technologies would likely provide the bulk of energy. The technologies considered here will simply be based on the current dominant sources of renewable and zero carbon energy on the UK grid shown in Figure 6.1 as the only other dominant zero carbon energy source.

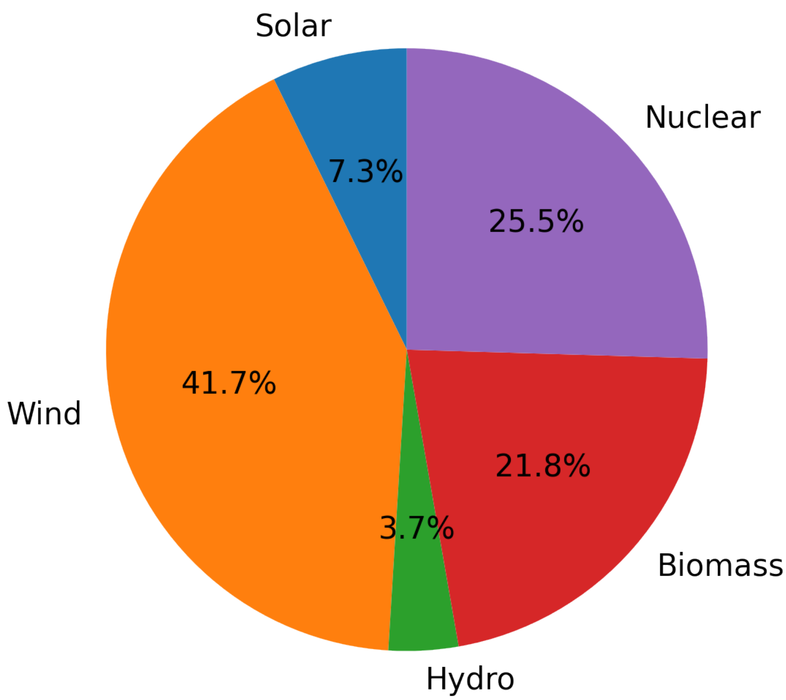

Figure 6.1: *Breakdown of UK zero carbon energy production (Wave/tidal Excluded due to low scale) in GWh for the year 2020-2021 based on UK government data [2]*

6.1 Solar

6.2 Offshore Wind

6.3 Nuclear

Nuclear energy has amongst the highest levelized Given the

6.4 Biomass

This section will be concerned with exploring the scalability and potential role that biomass may play in the future energy mix. For clarity, "biomass" in this essay will refer to a subset of generation types which produce energy from once living organisms [11] either by direct combustion or by generating gas through

[11] Note recently living i.e. not fossils

anerobic digestion.

A breakdown of the various technologies that constitute biomass energy is shown in Figure 6.2. The reader should note that the totality of this chart represents only roughly 12.6% of the total UK electrical energy production that energy in the year 2020 [10]. Many of these technologies vary substantially in their scalability and as such the following key technologies will be treated individually.

- Plant Biomass
- Anaerobic Digestion
- Energy from waste
- Landfill Gas

Other biomass technology will not be considered in this report due to it's expected low future utilization.

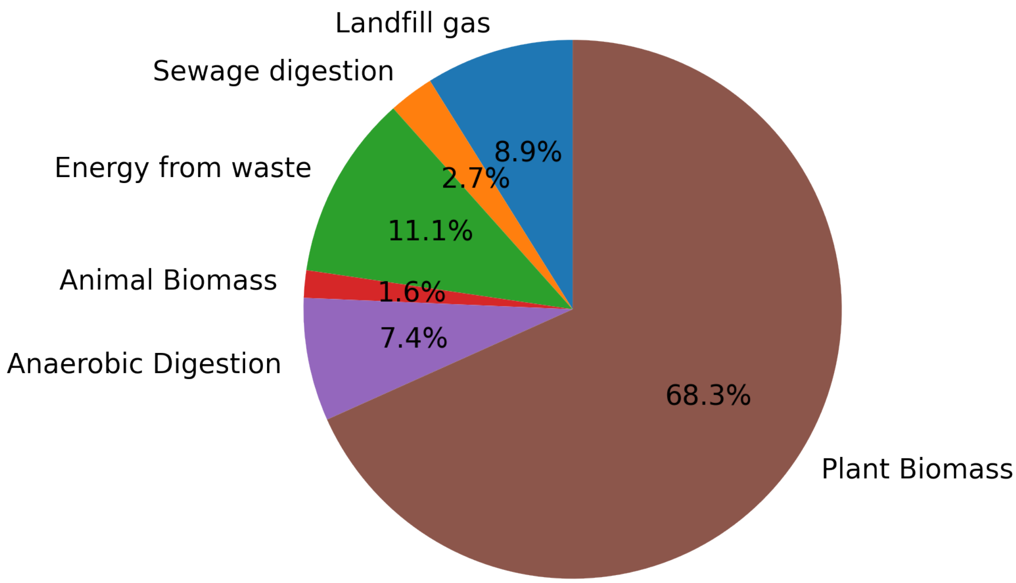

Figure 6.2: *Breakdown of "biomass" energy by type based on UK government data [2] (For tabular data see Section 9.7)*

6.4.1 Plant Biomass Combustion

Plant biomass combustion is by far the dominant form of Biomass generation in the UK accounting for ≈68.3% of total Biomass energy in the year 2020. The vast majority of this is in the form of wood bi-products and pellets imported from the united states and Canada [10].

Drax power plant is the largest biomass power plant in the UK, accounting for the vast majority of the UK's bio-energy production. The power station has six 660MW units, four of which were converted to purely biomass in 2016 yielding a total biomass capacity of 2.6GW. With the UK government's policy to phase out coal power by 2024 various plans were made to convert the remaining two units to gas and install carbon capture technology, however due to limited interest from the government, both plans have failed [11].

In theory, using such bio-fuels is net carbon neutral since the trees are harvested from managed woodlands which will regrow and recapture the emitted carbon, however there have been serious concerns raised about the transparency and traceability of the suppliers of these wooden pellets.

1. Scalability Currently the UK based biomass schemes are heavily reliant on foreign imported feedstock in the form of wood pellets. Indeed, Drax is the larges single buyer of such wooden pellets in the world. Not only does the shipping of these pellets incur carbon emissions, it also hints at another inherent limit of this technology, that being land surface area. With the large majority of the UK being farmland, only around 13% remains as forest, amounting to around 3.23 million hectares. The UK is already heavily dependant on foreign timber for the building sector, and wooden pellets imports have currently eclipsed these as the dominant import at 9.1million Tons [12].
   With the current generation demand for feedstock well outpacing domestic production with even this limited scale of operations currently providing only ≈8.6% of the current UK electricity demand, it is difficult to see how this technology will continue to scale. The UK is currently the leader in Biomass energy, however this technology is currently seeing rapid growth throughout Asia, America and the rest of Europe. Currently the production of these pellets is primarily limited to waste materials from wood mills meaning that the pellets are relatively low cost compared to timber. However as demand rapidly grows it seems highly likely that, producers will be increasingly forced to harvest timber purely to meet pellet demand driving up prices. Indeed there are already allegations that some of the largest producers of pellet feedstock are using whole trees, rather than the claimed waste material [13].
   Even though the UK is an outlier in it's overall population density it still seems unlikely that global forestry stocks could be a viable replacement for global fossil fuel consumption. Currently wooden pellets production in the United States only amount to around 8.6 million tons, only around ≈5% of it's total timber production[14, 15]. In some sense the early adopters of this technology are in somewhat of a catch 22, whereby if this technology does prove to be scalable and cost effective then there will certainly be much greater competition for feedstock acting to drive up the price.
2. LCOE According to figures from the figures from the Department of Business, Energy & Industrial Strategy, the LCOE of dedicated biomass is estimated at 98 £/KWh making it roughly ≈170% more expensive than offshore wind [3].
   It does however provide the interesting possibility of acting as a form of long term energy storage which may be dispatched to compensate from variable renewable sources. Another inherent benefit of this technology is that given it utilises large scale steam turbines driving synchronous generators is that it inherently also provides inertia to the grid, acting to improve the stability of the network as a whole.
3. Summary In summary, it is the authors view that while plant biomass may provide very limited carbon sequestration and energy storage, it seems unlikely that this technology could scale to replace the energy currently provided by fossil fuels. The numeric analysis of the prior section substantiates a long-held intuition of the author on biomass energy. That being: By combusting fossil fuels, industrial nations for the past ≈150 years have, in a relative eye-blink, consumed the stored residual energy of the biosphere which has been gradually accumulated over a period between ≈20-400 Million years. To think that this rate of energy consumption could be sated, even in part, by a fraction of it's instantaneous output , in the form of plant biomass, is unrealistic.

6.5 Interconnects

6.6 Impact

It is clear that a grid so heavily dependant on intermittent generation such as wind and solar, the available energy will fluctuate drastically both on a seasonal basis and on a relatively instantaneous basis. Though Offshore wind

7 Storage

7.1 Battery

7.2 Hydrogen Gas heating

8 Frequency Control Mechanisms

8.1 Current

8.2 Future

8.2.1 VSM

8.2.2 Synchronous Condensers

9 Appendices

9.1 Derivation of LCOE Breakdown

$$E_{Life}(CF) \propto CF \tag{9.1}$$
$$E_{Life}(CF) = k \times CF \tag{9.2}$$

Where k is a constant proportional to operational lifetime and nameplate rating.

$$k = S_{Base\ kW} \times t_{hours} \tag{9.3}$$

Substituting 9.1 into 3.1 we get 9.4:

$$LCOE = \frac{C_{Life}(CF)}{k \times CF} \tag{9.4}$$

We must note here that C_{Life} is itself a function of CF of the form:

$$C_{Life}(CF) = C_{Fixed} + C_{FuelLife}(CF) + C_{carbon\ Life}(CF) \tag{9.5}$$

The carbon cost of burning the fuel will be roughly proportional to the CF and may be defined with the constant β which can be defined in terms of the levelized cost of carbon ($C_{carbon(£/kWh)}$) for this given fuel taking into account the carbon efficiency of the fuel and the current carbon tax.

$$C_{carbon} = \beta \times CF \tag{9.6}$$
$$\beta = S_{base\ kWh} \times C_{carbon(£/kWh)} \times t_{hours} \tag{9.7}$$

$C_{FuelLife}$ May be defined in terms of the cost of fuel per unit Energy ($C_{Fuel/KWH}$) The operational lifetime of the plant in hours (t_{hours}) and the Base rating: (S_{Base}) for simplicity these factors are grouped into a term α:

$$C_{FuelLife} = \alpha \times CF \tag{9.8}$$
$$\alpha = S_{baseKW} \times t_{hours} \times C_{Fuel(£/KWH)} \tag{9.9}$$

Substituting 9.8 into 9.5 we get:

$$C_{Life}(CF) = C_{Fixed} + CF \times \alpha + \beta \times CF \tag{9.10}$$

Substituting 9.10 back into 9.4:

$$LCOE = \frac{C_{Fixed} + CF \times \alpha + CF \times \beta}{k \times CF} \tag{9.11}$$

Rearranging 9.12:

$$LCOE = \frac{C_{Fixed}}{k \times CF} + \frac{CF \times \alpha}{k \times CF} + \frac{CF \times \beta}{CF \times k \times CF} \tag{9.12}$$
$$LCOE = \frac{C_{Fixed}}{k \times CF} + \frac{\alpha}{k} + \frac{\beta}{k} \tag{9.13}$$

Substituting definitions of α and k from 9.8, 9.3 respectively:

$$LCOE = \frac{C_{Fixed}}{S_{Base\ kW} \times t_{hours} \times CF} + \frac{S_{baseKW} \times t_{hours} \times C_{Fuel(£/KWH)} + S_{base\ kWh} \times C_{carbon(£/kWh)} \times t_{hours}}{S_{Base\ kW} \times t_{hours}} \tag{9.14}$$

Cancelling:

$$LCOE = \frac{C_{Fixed}}{S_{Base\ kW} \times t_{hours} \times CF} + C_{Fuel(£/kWh)} + C_{carbon(£/kWh)} \tag{9.15}$$

9.2 Breakdown of a consumer energy bill

Table 9.1: *Ofgem Estimated components of customer's energy bills from Ofgem [7]*

VAT	Wholesale Price	Network Costs	Other Costs	Environmental/social obligation	Operating Costs
VAT 4.76	Wholesale Price 29.28	Network Costs 23.37	Other Costs 2.09	Obligations 25.48	Operating Costs 16.34

9.3 Breakdown of Levelized cost estimates

9.3.1 UK Gov data 2016

This Data is sourced from the UK Government Department of Business, Energy & industrial Strategy's 2020 Electricity generation Cost 2016 Report Table 4 (pg 27) [16].

Table 9.2: *Levelized cost Estimates for Projects commissioning in 2025, £/MWh (Data is sourced from UK Government Figures Published in 2016[3])*

	Nuclear PWR -FOAK	Coal - ASC with oxy comb. CCS -FOAK	CCGT with post comb. CCS - FOAK	Coal - IGCC with CCS - FOAK	CCGT H Class	OCGT 600MW (500hrs)	Offshore R3	Large Scale Solar PV	Onshore 5MW
Tag	Nuclear	Coal ASC+CCS	CCGT+CCS	Coal-IGCC+CCS	CCGT H	OCGT 600MW	Wind Off R3	Solar PV LS	Wind On
Pre-Development Costs	7	2	2	2	0	5	5	6	4
Construction Costs	66	72	41	78	7	63	69	49	42
Fixed O&M	11	11	5	12	2	17	23	8	10
Variable O&M	5	6	3	5	3	3	3	0	5
Fuel Costs	5	24	48	26	40	60	0	0	0
Carbon Costs	0	6	3	8	29	43	0	0	0
CO2 Transport and Storage [12]	0	17	7	18	0	0	0	0	0
Decommissioning and Waste	2	0	0	0	0	0	0	0	0
Total	95	136	110	148	82	189	100	63	61

9.3.2 UK Gov Data 2020

This Data is sourced from the UK Government Department of Business, Energy & industrial Strategy's 2020 Electricity generation Cost 2020 Report Table 4.3 (pg 26) [3][13].

[12]This name has been changed to from 'CCS cost' for compatibility with Table 9.3.

[13]Biomass data is appended from Table 8 in Annex 1: Additional Estimates[3].

Table 9.3: *Levelized cost Estimates for Projects commissioning in 2025, £/MWh (Data is sourced from UK Government Figures Published in 2020[3])*

	Offshore Wind	Onshore Wind Wind	CCGT H Class	CCGT+CCS Post Combustion - FOAK	Large-Scale Solar	Dedicated Biomass [13]
Tag	Wind Off	Wind On	CCGT H	CCGT+CCS	Solar	Biomass
Pre-Development Costs	3	3	1	0	3	2
Construction Costs	31	27	7	23	30	39
Fixed O&M	19	10	2	4	10	13
Variable O&M	3	6	4	5	0	9
Fuel Costs	0	0	40	45	0	35
Carbon Costs	0	0	32	3	0	0
CO2 Transport and Storage	0	0	0	4	0	0
Decommissioning and waste	1	0	0	0	0	0
Total	57	46	85	85	44	98

9.3.3 Process Data

```python
df_LCOE_2020 = pd.DataFrame(data2020).iloc[3:, :]
df_LCOE_2020.columns = data2020[2]

df_LCOE_2016 = pd.DataFrame(data2016).iloc[3:, :]
df_LCOE_2016.columns = data2016[2]
# display(df_LCOE_2016)
df_LCOE_2016 = df_LCOE_2016["Nuclear"]
df_LCOE_2Plot = pd.concat([df_LCOE_2020,df_LCOE_2016],axis=1, join="inner")
df_LCOE_2Plot=df_LCOE_2Plot.set_index("Tag").T
df_LCOE_2Plot = df_LCOE_2Plot.drop('Total',axis=1)

ax = df_LCOE_2Plot.plot.bar(stacked=true,rot=70,figsize=(11,6))
ax.set_ylabel("£/KWh")
ax=ax.legend(loc=2)
```

9.4 Capacity factor

This Table is Sourced from UK Government data [1, 2].

Table 9.4: *Load/Capacity Factor breakdown by generation technology from 2019 UK government data[16, 1]*

Technology	Capacity factor (%)	Source
Technology	Capacity Factor (%)	
Nuclear	63	[1]
CCGT	43	[1]
Hydro (Pumped)	7	[1]
Coal-fired	7.8	[2]
Wind On	26.5	[2]
Wind Off	40.4	[2]
Solar PV	10.9	[2]
Hydro	35.5	[2]
Plant Biomass	64.1	[2]

9.4.1 Process Data

```python
df_CF = pd.DataFrame(dataCF).iloc[1:,: ]
df_CF.columns = dataCF[0]
df_CF = df_CF.set_index("Technology")
# display(df_CF)
ax = df_CF.plot.bar()
out = ax.set_ylabel("Cappacity Factor (%)")
```

9.5 Zero carbon Energy Mix

Table 9.5: *Breakdown of UK Zero carbon energy production in GWh for the year 2020-2021 based on UK government data [2]*

	Solar PV	Wind	Hydro	Biomass	Nuclear	wave / tidal	total
GWh	13157.99	75369.14	6753.92	39311	46000	11.28	134592.05
Percent	9.8	56.0	5.0	29.2	34.2	0.0	

9.6 Current Natural gas demand

This data is sourced from the UK governments Digest of United Kingdom Energy Statistics 4.2 (DUKES)[4].

Table 9.6: *UK natural Gas Demand for 2019 Broken down by sector, Data sourced from UK Government [4]*

Sector	Consumption (GWh)	Consumption (%)
Electricity Generation	272331	31.55
Industry	165213	19.14
Losses	3410	0.40
Domestic+Public Sector + Commercial (Non Industrial)	377290	43.71
Other	44929	5.21
total	863174	100.00

9.6.1 Process Data

```python
data_NatGas = np.array(data_NatGas)
# display(data_NatGas)
labels = data_NatGas[1:-1,0]
labels = ['\n'.join(wrap(x,20)) for x in labels]
# display(labels)
sizes = data_NatGas[1:-1,1]
sizes = [float(x) for x in sizes]
# display(sizes)
fig1, ax1 = plt.subplots()
ax1.pie(sizes, labels=labels, autopct='%1.1f%%', startangle=90)
ax1.axis('equal')  # Equal aspect ratio ensures that pie is drawn as a
    ↪ circle.
plt.show()
```

9.7 Biomass/Waste Energy Breakdown

Table 9.7: *Breakdown of Energy generated from Biomass/Waste (GWh) according to UK government data [2]*

	Landfill gas	Sewage digestion	Energy from waste	Animal Biomass	Anaerobic Digestion	Plant Biomass (inc high range co-firing)	Total
	Landfill gas	Sewage digestion	Energy from waste	Animal Biomass	Anaerobic Digestion	Plant Biomass	Total
GWh	3496	1067	4352	647	2904	26845	39311
%	8.9	2.7	11.1	1.6	7.4	68.3	100.

9.8 US Forestry Production

```
df=pd.read_csv('UnitedStatesForestry.csv')
display(df.columns)
df=df[(df["Unit"]=="tonnes")&(df["Flag"]=="Im")&(df["Element"]=="Production")]
display(len(df))
```

10 Bibliography

References

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